Future expansion of agriculture and pasture acts to amplify atmospheric CO_2 levels in response to fossil fuel and land-use change emissions (Climatic Change, in press)

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Abstract. The expansion of crop and pastures to the detriment of forests results into an increase in atmospheric CO_2. A first obvious cause is the loss of forest biomass and soil carbon during and after conversion. A second, generally ignored cause, is the reduction of the residence time of carbon when for example forests or grasslands are converted to cultivated land. This decreases the sink capacity of the global terrestrial biosphere, and thereby may amplify the atmospheric CO_2 rise due to fossil and land-use carbon release. For the IPCC-A2 future scenario, characterized by high fossil and high land-use emissions, we show that the land-use amplifier effect adds 61 ppm extra CO_2 in the atmosphere by 2100 as compared to former treatment of land-use processes in carbon models. Investigating the individual contribution of each of the 6 land-use transitions (forest ↔ crop, forest ↔ pasture, grassland ↔ crop) to the amplifier effect indicates that the clearing of forest and grasslands to arable lands explains most of the CO_2 amplification. The amplification effect is 50% higher than in a previous analysis by the same authors which did not consider neither the deforestation to pastures nor the ploughing of grasslands. Such an amplification effect is further examined in sensitivity tests where the net primary productivity is considered independant of atmospheric CO_2. We also show that land-use changes which have already occurred in the recent past have a strong inertia at releasing CO_2, and will contribute to about 1/3 of the amplification effect by 2100. These results suggest that there is an additionnal atmospheric benefit of preserving pristine ecosystems with high turnover times.

1. Introduction

Over the recent past, changes in land-use, mainly the clearing of forests to crops and pastures, have generated emissions of CO_2 to the atmosphere of similar magnitude than those caused by fossil fuel burning. Yet the fluxes of carbon induced by land-use and land cover changes are very uncertain to estimate. A difficulty is that one must account not only for the initial loss of carbon following conversion, but also for the delayed fluxes, which can evolve from an initial source to a later sink after recovery or regrowth of secondary ecosystems. In addition to releasing CO_2, which eventually gets redistributed among the atmosphere-ocean-land biosphere pools, land-use processes also modify the residence times of carbon in ecosystems. Following conversion, such residence times may decrease as when forests are cleared for pastures or croplands, or increase, as when croplands are abandoned or afforested. Thus, land-use change leads to atmospheric CO_2 increase in two ways: directly because of the net carbon loss during and after conversion, and indirectly because it reduces the global sink potential of the terrestrial biosphere, due to reduced turnover times of excess carbon.

To illustrate this, we have constructed a spatially aggregated, parameter-scarce global carbon cycle model, where atmospheric CO_2 is calculated as a function of fossil emissions and land-use induced ecosystem area changes. This reduced model accounts for major types of ecosystems (crops, pasture, forests) and for conversions among them, in 4 world regions. First, we describe the model and its input data for changes in area of the different ecosystems. Next we model the land-use source to the atmosphere over the historical period and evaluate it against the observed atmospheric CO_2 increase, and identify the contribution of each type of conversion to it. Third, we make future CO_2 calculations based upon a land cover change scenario from the IPCC. In the discussion, we analyze through specific sensitivity tests which type of land-use and land cover process has the largest amplifying effect on future CO_2 trajectories.

2. Land-use model description

2.1. Basic components

Our carbon cycle model consists of reduced-form ocean model and of a parameter-scarce terrestrial model described in (Gitz and Ciais, 2003) hereafter referred to as GC2003. The ocean uptake of anthropogenic CO_2 is calculated following (Joos et al., 1996) from mixed-layer ocean pulse response functions. The terrestrial carbon model is simplified from CASA-SLAVE (see details in GC2003), and distinguishes 9 biomes: 3 forest biomes, 3 crop types and 3 pasture (or grasslands) types, in function of climatic attributes (boreal, temperate, tropical, see Table I). The terrestrial model includes a relatively detailed land-use module that defines cohorts of lands in transition between pairs of biomes, and calculates the net CO_2 flux to or from the atmosphere associated with land-use changes, which sometimes lasts for decades after the initial disturbance.

Four world regions, as defined by the Intergovernmental Panel of Climate Change Third Assessment Report (IPCC-TAR, (Prentice, 2001)) : OECD-1990 (North America, Europe, Japan and Australia), REF (Former Soviet Union and Eastern Europe), ASIA, ALM (Africa, Latin America and Middle East) are considered. In each IPCC region, the 9 biomes can be grouped according to climatic caracteristics (temperate, boreal and tropical), defining three "climatic zones" by region. In total, this sets up 12 "grid-points", each of them shared by three "undisturbed" land cover types and annually-defined cohorts of lands in transition between them. Within each-grid point, we follow the area, the biomass content, and the soil carbon content of each "undisturbed" biome, and of each individual cohort of lands in transition. This defines typically $2 \times (3 + 6\tau)$ carbon reservoirs per grid point, with τ being the duration, in years, of a land-use transition (typically $\tau \sim 100$ years). Two wood products pools per grid point are also defined, to account for the harvest of wood during deforestation. The whole formalism is given in the Appendix. Net Primary Productivity (NPP) is modeled to increase under rising CO_2 according to a β-factor formulation (see equation 2), with the value of $\beta = 0.52$ being adjusted to match the observed global carbon budget 1980-2000. The sensitivity of our results to different assumptions, in particular to the case where NPP is not dependant on CO_2, will be examined. Constant climate is assumed to let estimate specifically land-use effects on atmospheric CO_2. Thus, in this study, the particular impact on climate change to terrestrial carbon-cycling is not considered.

2.2. Model set up and results for areas

We have made a major improvement to the original GC2003 model. Namely, we added grasslands as a specific biome undergoing land-use change. Hence grasslands $\leftrightarrow$ forests and grasslands $\leftrightarrow$ croplands transitions are treated, instead of forests $\leftrightarrow$ croplands transition alone. Pastures and grasslands form one unique biome in the model, in the sense that we model them to have the same NPP, biomass mortality

Table I. Areas of key biomes for the 4 IPCC regions, in 1700, 1990 and 2100, unit: 10^6 ha

	OECD			REF			ASIA			ALM		
Year	1700	1990	2100	1700	1990	2100	1700	1990	2100	1700	1990	2100
temperate forests	600	530	419	212	145	157	408	397	346	625	602	537
boreal forests	778	767	756	1249	1249	1249	114	114	114	61	61	61
tropical forests	52	44	34	-	-	-	455	269	88	1126	679	52
temperate crops	-	243	544	-	211	310	-	38	133	-	20	147
boreal crops	-	11	39	-	-	-	-	-	-	-	-	-
tropical crops	-	60	96	-	-	-	-	186	499	-	315	1498
temp. past. & grass.	511	336	147	722	578	467	513	485	441	70	73	11
boreal past., tundra	513	513	495	514	514	514	43	43	43	-	-	-
tropical past. & grass.	625	573	547	-	-	-	309	309	177	2308	2440	1885

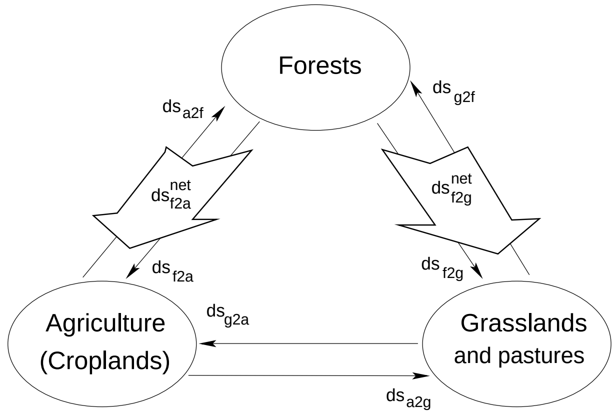

Figure 1. Land-use transitions accounted for in the model, within a model "grid-point", defined by the particular IPCC region (OECD-90, REF, ASIA, ALM) and a climatic zone (temperate, tropical or boreal). Land-use transitions do not occur across such grid points. General scheme with 6 gross transitions, as used for historical period. In the future period, grid-point by grid-point and at each time-step, only net transitions were implemented, as deduced from IMAGE 2.2. Such net transition are represented with big arrows, in the case where forest area diminishes and agricultural and grasslands area increases within the pixel at one time step.

and soil respiration rates, as regionally averaged from CASA-SLAVE grid-point values for grassland biomes.

Let ds_{x2y} be the amount of land converted from land-use class $x = f, a, g$ (for forest, agricultural land, grassland) to land-use class $y = f, a, g \;\; y \neq x$, within one competing grid-point, and at a particular time step. Over the historical period 1700-2000, such values of ds_{x2y} are annually prescribed following (Houghton and Hackler, 2001), as illustrated in Figure 1. For the future, the evolution of grasslands, forests, and croplands is taken from the IMAGE 2.2 model results for IPCC A2 scenario. This particular scenario has relatively high fossil emission rates (fossil emission peaks at 26 GtC/yr in 2100), and is also a land-use intensive scenario, because of high population growth in developing countries, and relatively weak expansion of trade between regions, with the consequence that, locally, forests and grasslands need to be converted to arable lands.

Within each grid-point, IMAGE 2.2 does not directly give the values of ds_{x2y}, but only the net area change of each biome. Hovewer, the six values of ds_{x2y} can not be univoquely deduced from the 3 net area change values in one grid-point at one time-step. Given such a particular net area change, several transitions schemes ds_{x2y} are acceptable. We decided to select the one that minimizes the grid-point area subject to land-use change: if two land-use classes gain surface in disfavor of the third one, we defined only two non-zero transitions from the diminishing class to the increasing ones (such a case is represented in Figure 1 with big arrows). Conversely, if one land-use class gains surface, whereas the two other lose surface, we defined only two non-zero transitions from the two diminishing land-use types in favor to the increasing one. This particular construction of the transition matrix defines the "minimum" land-use transition coherent with the input of IMAGE 2.2 areas evolution.

The resulting evolution of global land-use transition rates (in Mha/yr) are given in the left handside of Figure 2. Cumulated global area change values, for each particular transition, can be found in Table IV. Overall, both natural grasslands and forests lose surface over time in favor of crops (Figure 2bc). Their contribution to supply new agricultural lands, both over the historical period and into the future is approximately equal. In comparison, the loss of forest area to grasslands is of smaller magnitude (Figure 2a), except in South America, where this transition was significant during the 1960's, at rates peaking at 3.5 Mha yr^{-1}. In the recent past, deforestation to croplands mostly occurred in tropical regions (ASIA and ALM), whereas the ploughing of grasslands into crop fields mostly took place in the OCDE and REF regions, dominated by temperate ecosystems. For instance, the conversion of US Great Plains to agriculture between 1850 and 1930, at rates between 1.2 and 1.8 Mha yr^{-1}. By 1950, there was a step increase in grassland losses which corresponds to the launch of massive cultivation programs in Former Soviet Union, at rates as high as 5.7 Mha yr^{-1}.

In the future, the A2 scenario drivers are a large increase in global population, with little trade and interactions among countries. This has the effect to convert a great part of Africa's savannas and forests into arable lands, as illustrated in the curves of Figure 2b. For the period 2020-2070, the A2 scenario projects new expansion of forests over grasslands in temperate regions (OCDE and REF, 69 Mha). By 2100, the respective global loss of forest and grassland in favor of agriculture are about similar, close to 10 Mha y^{-1} in the A2 scenario. The peak in forest-to-cropland and grassland-to-cropland net losses occurs between 2000 and 2030, associated with the largest population rise in the A2 scenario, with grassland-to-cropland maximum conversion rates reaching up to 22 Mha yr^{-1}.

The global gross area changes can be compared with the net area changes they result from, as shown in Figure 2a-c. In the case of the forest $\leftrightarrow$ grassland transitions, a gross area change via afforestation is modeled in 2020-2050, but is otherwise negligible compared to the gross loss of forests in favor of pasture (Figure 2a). In the case of croplands

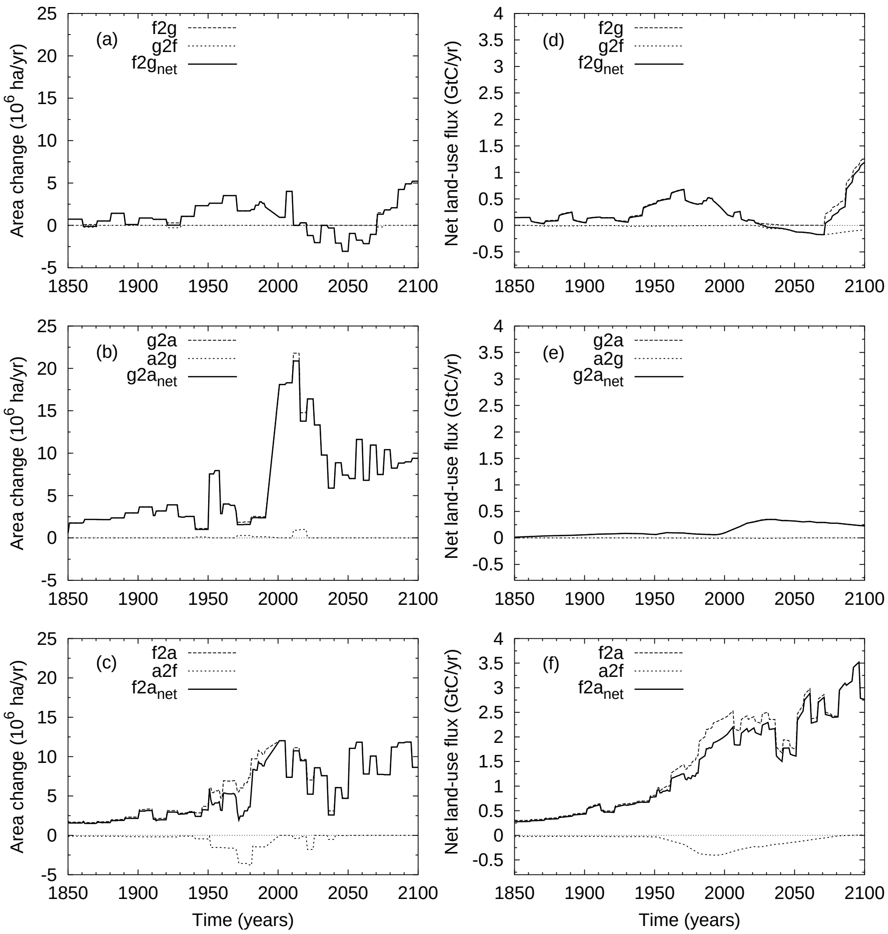

Figure 2. (left) Global yearly changes in areas between pairs of biomes involved in land-use change for : (a) grasslands-forests ; (b) grasslands-crops ; (c) forest-crops. (right) Net carbon fluxes exchanged with the atmosphere for : (d) grasslands-forests ; (e) grasslands-crops ; (f) forest-crops. Solid lines describe the overall net area change between a pair of biomes. Dash and dotted lines describe the gross area changes as illustrated in Figure 1. The notation $x2y$ means "transition from biome x to biome y".

↔ grasslands transitions, the gross restoration of arable lands into grasslands is about zero in the scenario (Figure 2b). Only for the forest ↔ cropland transitions, and during the historical period, do gross area changes matter. Between 1950 and 2010, forest regrowth after agricultural abandonment in Europe, FSU and in the US, plus afforestation programs in China during 1950-1980 (annual rates between 1.4 and 2.4 Mha yr^{-1}) offset about 50% of the deforested areas in Tropical Asia and Tropical America. However, in the future, agricultural abandonment

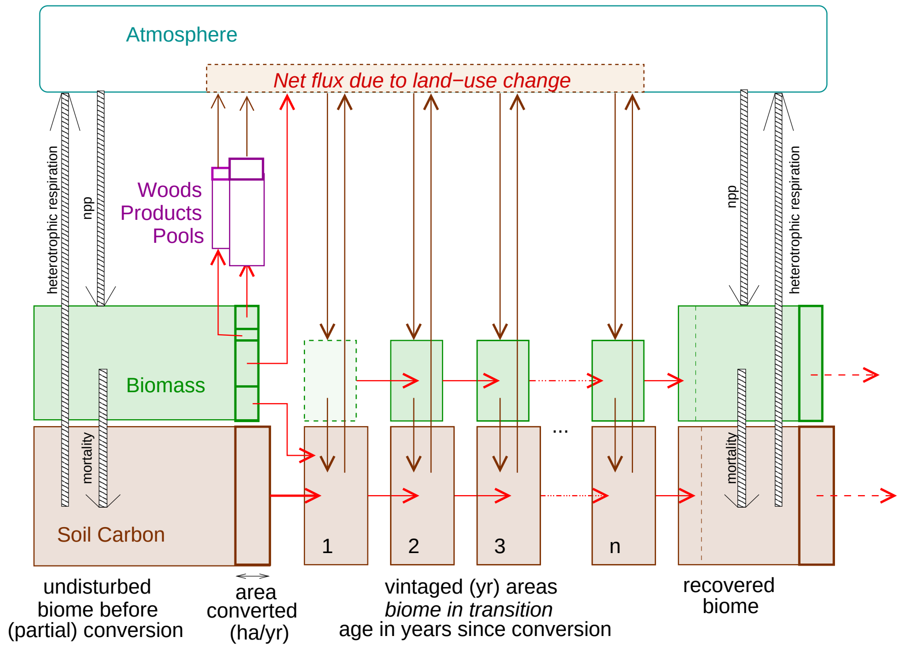

Figure 3. Schematic representation of the terrestrial carbon stocks and fluxes calculated in the model, within a particular grid point, and for a particular transition (here forest to grasslands). Equations for computing areas, stocks and fluxes are given in the Appendix.

does not occur in the high land-use A2 scenario, because of the strong demand on arable land exerted by an ever increasing population.

2.3. Model set up and results for land-use induced carbon fluxes

The carbon flux to or from the atmosphere induced by land-use changes are calculated using a “book-keeping” method. This is done by defining cohorts of increasing age classes after conversion, and computing their carbon-content, up until some “carbon equilibrium” state is reached, and the ecosystem in transition re-enters an “undisturbed” pool. The word “carbon equilibrium” means that the ecosystem is carbon-neutral with respect to the atmosphere if CO_2 level is constant. Details of the book-keeping model are given in the Appendix. As shown in Fig. 3, the flux associated to land-use change is defined as the sum of (i) an “instantaneous” flux occurring the year of the transition, plus (ii) the net flux to the atmosphere over the surfaces in transition, and (iii) flux resulting of decaying wood products.

For example, following the clearing of forests to agriculture, a fraction (70%) of the standing biomass is lost to the atmosphere within the first year, the harvested wood (30%) is directed into mid-term and long-term reservoirs of products, and the former forest soils lose carbon to the atmosphere up until they equilibrate with the new input of agricultural NPP. In contrast, a conversion of grasslands to agriculture does only impact significantly the soil carbon stocks.

A newly converted land is assigned the NPP, mortality and respiration rates of the corresponding new biome. NPP of croplands was assigned the world average value determined by (Goudriaan et al., 2001) from agricultural statistics (334 $g/m^2/yr$). Using distinct crop NPP values for each region in the model would not improve the results, since Goudriaan have reported differences no larger than 20% among NPP of 7 major crop types over the globe, representing 81% of the world cultivated area. We assumed that 70% of the annual crop NPP, representing harvest and fastly oxidized products, is oxidized in the year following harvest, whereas the remaining 30% is delivered to the soil as litterfall. For grasslands, mortality of biomass is taken from CASA-SLAVE (see Table II). We also made the assumption that NPP of pastures equals the one of natural grasslands within each region. For both grasslands and pastures, the oxidation of a fraction of NPP by herbivores was ignored.

As compared with GC2003, we improved our parameterization of the residence times of carbon in cropland soils, which was previously set equal to the one of the grasslands. Focusing on the grassland to crop conversion, this former assumption would lead to a likely underestimate of equilibrium cropland soil carbon stocks. Indeed, equilibrium carbon stocks in soils are entirely determined by the equilibrium mortality flux and the respiration rate δ, expressed as a percentage of the carbon stock in the soil. If croplands and grasslands were supposed to respire identically (same δ), then the ratio of equilibrium soil carbon stocks of crop fields relative to the ones of grasslands would be equal to the ratio of litter input to the soils, which may be as low as 0.2. In reality average soil respiration rate is reduced after grassland to cropland conversion, as it is after deforestation. Thus, we decided to adjust the respiration rate of cropland soils (see values reported in Table II) in such a way that the cropland to grassland ratio of soil carbon stocks is close to 0.5 over each region, a value close to the one of the survey of (Guo and Gifford, 2002).

In Figure 2d-f, we show the carbon fluxes resulting from changes in area given in the left-hand side of the same figure. Roughly, the evolution of the carbon flux follows the one of the areas, but it is smoother because of delayed emissions following any change in land-

Table II. Parameters averaged over each region as derived from the CASA-SLAVE model that are used in the reduced-form terrestrial carbon model. $\mathrm{NPP}^{t=0}$ is the net primary productivity in 10^6 ha, $\mu^{t=0}$ the biomass mortality in g/m^2/yr, and $\delta^{t=0}$ the soil respiration rate for pre-industrial conditions in %/yr.

	OECD			REF			ASIA			ALM		
biome	$\mathrm{NPP}^{t=0}$	$\mu^{t=0}$	$\delta^{t=0}$	$\mathrm{NPP}^{t=0}$	$\mu^{t=0}$	$\delta^{t=0}$	$\mathrm{NPP}^{t=0}$	$\mu^{t=0}$	$\delta^{t=0}$	$\mathrm{NPP}^{t=0}$	$\mu^{t=0}$	$\delta^{t=0}$
temperate forests	593	7.47	5.16	451	11.25	5.79	671	5.92	4.15	1000	5.75	3.88
boreal forests	460	9.38	5.18	275	14.69	6.83	829	5.90	3.26	377	9.50	5.04
tropical forests	884	12.84	9.42	-	-	-	884	6.05	5.25	1000	6.09	4.38
temperate crops	334	30.00	3.13	334	30.00	4.82	334	30.00	4.67	334	30.00	4.67
boreal crops	334	30.00	5.71	334	30.00	17.17	334	30.00	2.15	-	-	-
tropical crops	334	30.00	13.92	-	-	-	334	30.00	1.77	334	30.00	1.79
temp. grass. & pastures	266	33.99	4.44	98	10.66	2.31	221	38.69	4.96	-	-	-
tundra and boreal pastures	58	6.92	1.57	83	30.17	6.27	305	21.81	3.60	-	-	-
trop. grass. & pastures	253	37.20	15.39	-	-	-	519	8.89	4.40	570	9.13	4.84

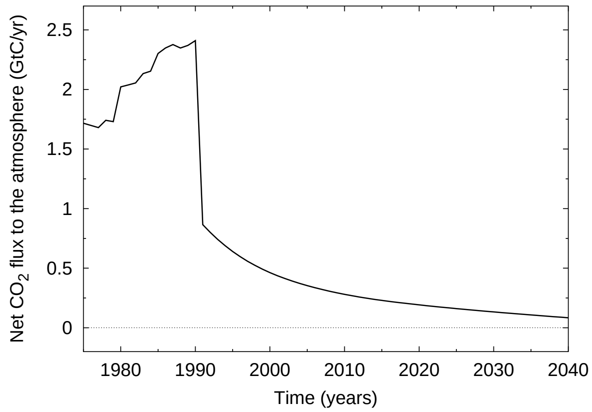

Figure 4. Evolution of the modeled land-use source in a model run where all land-use change activities are stopped in 1990.

use (see Figure 2e for the conversion of grasslands to crops). It can be seen that for a similar change in area, the conversion of forest to agriculture (Figure 2f) yields a larger source of CO_2 to the atmosphere than does the conversion of grassland to agriculture (Figure 2d). This is because forests soils stocks are larger than grasslands stocks prior to crop establishment (GC2003, Table B1). As expected, the afforestation of grasslands (Figure 2d) and the abandonment of agriculture yields to a net carbon sink from the atmosphere. That sink occurs after 2020 for the afforestation or reforestation of grasslands (Figure 2d), and between 1950 and 2000 for agricultural abandonment. Overall, the global source of land-use is of 1.5 GtC yr^{-1} in 1950, increases up, to 2.4 GtC yr^{-1} by 1990 (both slightly higher values than Houghton's) and culminates at 4.2 GtC yr^{-1} by 2100. Its cumulative value amounts to 72% of the total fossil fuel emissions by 2000 (199 GtC, a slightly higher value than reported in IPCC-TAR), and 25% by 2100. It should be noted that, unlike for an abrupt stop in fossil fuel emissions, even if land-use changes would stop abruptly, the delayed emissions from recently converted soils would significantly continue for up to 30 years before going down to zero. Such global net cumulative "tail" flux for post 1990 emissions is of 18 GtC, an amount equivalent to about 10 years of net land-use emissions at current rates (Figure 4).

3. Simulating the historical period

3.1. Land-use source

Our modeled land-use source is compared with the one of (Houghton and Hackler, 2001) for the historical period in Figure 5. While staying globally within the 30% uncertainty range of the results of (Houghton and Hackler, 2001), our model nevertheless overestimates their land-use source in the Tropics by an amount of up to 0.5 GtC/yr (Figure 5c). Also note that the modeled tropical source is up to 30% greater than in GC2003, for the 1940-1970 period, because we account now for the deforestation to pastures: globally 222 Mha since 1700, all in the ALM region that includes South America, a surface equal to 23% of the global deforested area since 1700. However, our new parameterization of turnover times in cropland soils (see former section) reduces the mismatch with Houghton et al. concerning the loss of soil carbon after land-use change (typically 10 to 40 tC/ha in Houghton depending on the transitions), a quantity that was probably overestimated in GC2003. So, overall, this new land-use module predicts only a slightly higher source compared to Houghton.

In the temperate region we obtain a lower carbon release due to land-use change than Houghton (Figure 5b), mainly because of a discrepancy in the biomass density of temperate forests: 7.4 kg/m^2 in our model, as resulting from biome-specific regional average of CASA-SLAVE grid-point values, vs. 13.5 kg/m^2 in Houghton. However, the temperate land-use source, which was much lower than Houghton's estimation in GC2003 is now in better agreement, because we account in this work for the 396 Mha of grasslands that were turned to agriculture in North America, plus 60 Mha in Europe. Such massive conversion of grasslands to crops is modeled to have caused a net cumulated release of carbon of 11 GtC to the atmosphere during 1700-1990. In comparison, over the same period, the conversion of 742 Mha of forests to cropland was modeled to release a cumulated 137 GtC.

3.2. CO_2 budget

At each annual time step, we compute the net land-use source, the net biospheric uptake (over undisturbed or recovered forests and grasslands) and the ocean sink. The resulting atmospheric CO_2 rise closes the CO_2 budget, given prescribed fossil fuel emissions. Figure 6 shows the evolution during 1850-1990 of the global sources and sinks to the atmosphere. The pertaining atmospheric CO_2 curve is compared to the measured concentration, giving reasonable agreement: this result is dependent on affecting a particular value to the β factor ($\beta = 0.52$)

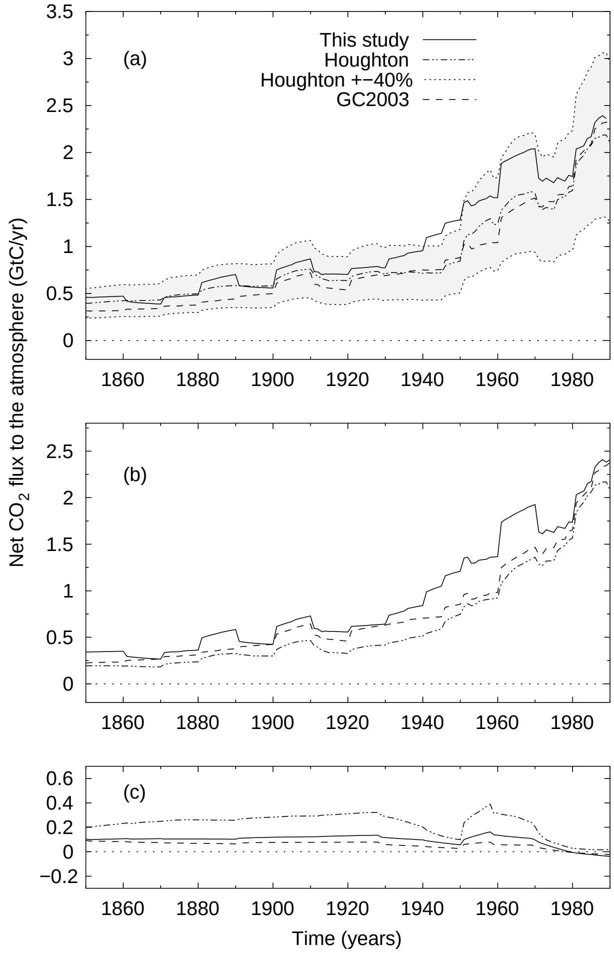

Figure 5. Comparison between the historical net land-use CO_2 flux calculated by our model as compared to the one of Houghton et al, 2001. (a) Globe, (b) "tropical" regions (ASIA+ALM), (c) "boreal and temperate" regions (OCDE+REF). The two calculations are forced by the same area changes, but differ in their carbon parameterizations.

controlling CO_2 fertilization (Equation 2). However, the value of atmospheric CO_2 between 1880-1960 is underestimated by 10-15 ppm using a single value of β and without taking into account other effects such as N-deposition (Friedlingstein, 1995; Friedlingstein et al., 1995), or variability and trends in climate (Cannell, 1999), that might modulate the uptake of carbon by the biosphere. Inclusion of land-use processes where grasslands and pastures are involved brings the modeled CO_2

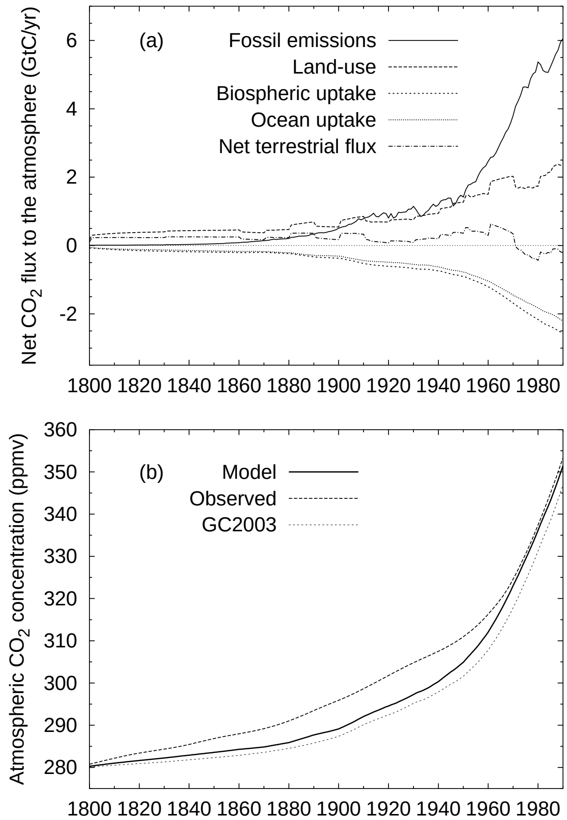

Figure 6. (a) Modeled historical changes in the component fluxes of the carbon budget and, (b) modeled and observed atmospheric CO_2 concentration curves between 1800 and 1990.

closer to the observed historical curve, but it is not sufficient to match the ice-core observations, as shown in Fig. 6b.

Our results over the historical period are also coherent with IPCC-TAR estimates for the 1700-1990 cumulated budget and with the average global carbon budget of the 1980's, as shown in Table III. Table III compares the modeled carbon balance for the 1980's with the IPCC-TAR: in the period 1980-1989, the global ocean uptake is of 2.01 GtC/y, in agreement with the IPCC-TAR estimates.

4. Projecting the future

We performed two simulations of the CO_2 trajectory between 1900 and 2100. In the first one, called E1, land-use processes are interactive with

Table III. (left) Average carbon budget for the period 1980-1989 and, (right) cumulated changes in carbon reservoirs in our model and in IPCC-TAR and IPCC-SRLULUCF estimates. By convention, sources are positive and sinks are negative.

	1980's av. flux (GtC/yr)		*1850-1998 cum. flux (GtC)*	
	Model	*IPCC-TAR*	*Model*	*IPCC-SRLULUCF*
Atmospheric increase	3,28	3,3 ± 0.1	172	160
Fossil emissions	5,45	5.4 ± 0.3	268	270 ± 30
Ocean uptake	-2,03	-1,9 ± 0,6	-115	-120 ± 50
Land atmosphere flux	-0,18	-0.2 ± 0.7	26	26 ± 60
partitioned as follows				
land-use emissions	2,21	1.7 (0.6 to 2.5)	161	136 ± 55
Terrestrial sink	-2,39	-1.9 (-3.8 to 0.3)	-135	-110 ± 80

the carbon cycle, with our model being forced by fossil emissions and by land cover changes in area. In the second run, called E2, a land-use source identical to the one of E1 is injected into the atmosphere, the land cover being kept constant at its pre-industrial state. So, in E2, the land-use source is treated as fossil fuel emissions, as done in former IPCC-TAR calculations. It is expected that, in experiment E2, the atmospheric CO_2 concentration level will be lower, because the continental biomes are more efficient in absorbing excess CO_2 than in E1. Thus, land use change, like deforestation, injects CO_2 into the atmosphere (Figure 2), but also reduces the sink capacity of terrestrial ecosystems by shortening the residence time of an excess carbon in ecosystems. The reduction of terrestrial uptake in E1 *vs* E2, as modeled to be driven by CO_2 fertilization alone and reported in Figure 7, causes atmospheric CO_2 to be higher by up to 61 ppm in E1 than in E2.

We observe that the biospheric uptake is already larger in E2 than in E1 by 0.45 GtC y-1 in 2000. This effect increases with time, as land-use impacts an ever increasing area of forests, with a terrestrial sink of 8.4 GtC y-1 in E2, compared to 5.4 GtC y-1 only in E1. This amplifying effect of land-use changes on atmospheric CO_2 is of the same order of magnitude than the role of climate feedbacks recently evaluated in coupled GCM-carbon cycle modeling studies. Such a two-fold role of land-use processes in increasing CO_2 (source of CO_2, sink capacity reduced) has been neglected in former studies (eg IPCC-TAR) considering the land cover to be pre-industrial.

There is a small negative, stabilizing, feedback in our system because both the ocean and pristine ecosystems are modelled to sequester

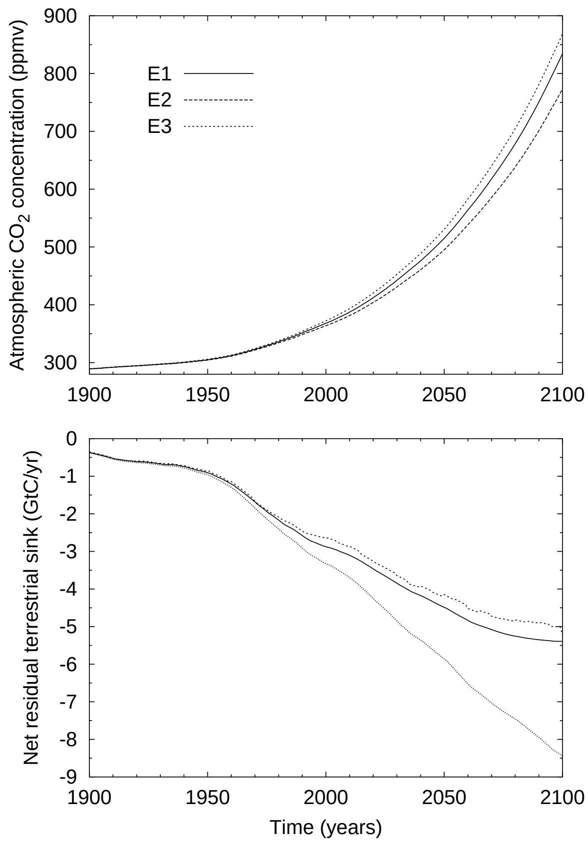

Figure 7. (a) Atmospheric CO_2 curves calculated in response to fossil fuel emissions and land-use induced carbon fluxes under the IPCC A2 scenario. E1 treats land cover changes consistently with the rest of the carbon cycle whereas E2 assumes pre-industrial land cover and land-use net emissions from E1, (b) Corresponding residual terrestrial sink over ecosystems not involved in land-use changes.

more carbon if CO_2 rises faster, which happens in E1. To evaluate the magnitude of this stabilizing feedback, that is self-contained in E1, we performed a third model simulation called E3. E3 is strictly identical to E1, with the exception that ocean and terrestrial ecosystems “see” the low atmospheric CO_2 trajectory of E2. Hence, atmospheric CO_2 in E3 is the highest of all (Figure 7). The difference between E3 and E1 estimates the magnitude of the stabilizing feedback by which the ocean and undisturbed ecosystems act to slightly counterbalance the “gross” amplification (estimated by E3 - E2) of land-use change on atmospheric CO_2. In the IPCC A2 scenario, the stabilizing feedback is of 34 ppm compared to the net amplifying “effect” estimated by E1 - E2 to be of

61 ppm. In addition, considering that large uncertainties pertain to that stabilizing feedback, due to possibly no strong effect of CO_2 fertilization in driving terrestrial uptake (Caspersen et al., 2000), or due to ocean sink weakening in the coming decades (Bopp et al., 2001; Bopp et al., 2002), it is likely that the feedback will always remain much smaller than the amplifier effect.

Note that land-use changes compete with climate feedbacks to suppress tropical forests. In climate-carbon studies, climate change has a negative impact on the productivity of undisturbed tropical forests, causing their dieback, and turning, for example, the Amazon into a net source to the atmosphere (Cox et al., 2000). But, because of land-use changes, the remaining area of undisturbed tropical forests vulnerable to climate change induced dieback might be smaller. This is already true by 1990, in the sense that, a cumulated 646 Mha of tropical forests have already been deforested, an area representing 40% of their preindustrial extent, and is likely be confirmed in IPCC A2 scenario, in which very few undisturbed tropical forests subsist, typically only 10% of the preindustrial extent (see Table I). It is also possible that ecosystems primarily impacted by climate feedbacks will not be much affected by land-use, which might be the case in boreal regions. So, globally, in terms of evolution of terrestrial carbon stocks and atmospheric CO_2 rise, the two indirect effects of (i) land-use change amplifier and (ii) climate feedbacks, as evaluated separately, may be partially additive.

As modeled, NPP increase is directly function of atmospheric CO_2, but there is a potential bias of attributing to CO_2 such an increase which might be related to other factors (N-redeposition, climatic effects), and/or that might not persist in the future. We examined the sensitivity of the amplifier effect to three different cases, where future NPP increase is not related to CO_2. In the first case (a), the NPP of each biome is kept constant after 1990. In case (b), NPP increases linearly with time up until 2100, the annual increment being equal to the modeled average annual increment during the XXth century, namely $+0.0010049 \times NPP(t = 1700)$. Case (c) is identical to (b) up until 2030, after which NPP is kept constant. Results are shown Table IV. The amplification effect attributed to land-use is reduced in all cases, but the biosphere is also a less stronger sink. In consequence, in all those experiments, the airborne fraction of both fossil and land-use emissions is higher, and absolute atmospheric CO_2 levels are much higher, as compared to when assuming the existence of a certain extent of CO_2 fertilization in the future. If, for any reason, net primary productivity of ecosystems does not increase in the XXIst century (case a), atmospheric CO_2 is modelled to be 150 ppm higher than with the initially modeled

Table IV. Sensitivity of the amplification effects to different hypothesis relative to the mecanisms creating an increase in NPP. Units: ppmv. (text) Amplification effect with NPP function of CO_2, with $\beta = 0.52$. (a) Historical NPP as in (text), but no increase in NPP after 1990. (b) Historical NPP as in (text), and NPP increasing linearly with time after 1990, the annual increase set equal to the average annual increase between 1900-1990. (c) Same as (b) until 2030, NPP kept constant after 2030 to its 2030 value.

	atmospheric CO_2 (E1, 2100)	E1-E2	E3-E1
(text)	834	61	34
(a)	985	11	7
(b)	946	29	11
(c)	973	16	9

CO_2 fertilization and $\beta = 0.52$, and the land-use amplifier effect is then a second order effect.

4.1. Attributing the amplifier effect to different transition types

In order to evaluate separately the role of each land-use transition (Figure 1a) to the amplifier effect, we made 6 different experiments, where only one gross transition is considered at a time during the whole 1700-2100 period. The results are compared with a “control” run which includes all transitions together, and with a “zero” run, where land-use transitions are excluded (Table V).

The amplification effect we want to assess here is clearly due to land-use: the “zero” simulation with no land-use for the whole period 1700-2100 leads to the same atmospheric increase both in E1 and E2 (+383 ppm by 2100 as compared to 1700). This amount is equal to the contribution of cumulated fossil-fuel emissions to atmospheric CO_2 increase during this period. Conversely, the contribution of land-use changes during 1700-2100 to the excess of atmospheric CO_2 by 2100 is of 171 ppm in E1, and 110 ppm in E2 (differences in atmospheric CO_2 levels by 2100 between the “control” and the “zero” simulations). The 61 ppm difference is the amplification effect, therefore not negligible in relation of the overall contribution of land-use for 1700-2100. The relative difference E2-E1/E2 is as high as 55% in the A2 scenario, suggesting that one GtC emitted by land-use change may contribute in proportion more to increase atmospheric CO_2 than one GtC emitted via fossil fuel burning. This effect is equivalent to increasing the airborne fraction of cumulated fossil fuels emissions in 2100 from 55 % (E1) to

Table V. Separate contribution of each land-use transition to the atmospheric CO_2 increase. Left : 1700-2100 period, Right : 1990-2100 period only, given "control" run in the past period. In the "control" case, all land-use transitions occurs altogether (as in Houghton et al., 2001, or as derived from IMAGE 2.2). In the "zero" case, during the considered period, land-use transitions are suppressed. (area): cumulated area subject to land-use change in 10^6 ha. (flux): cumulated land-use flux in GtC. Note that for the 1990-2100 period, all individual $x2y$ simulations contain the tail of historical "control" emissions stopped by 1990 as in Figure 4 (18 GtC), so that the sum of cumulated emissions 1990-2100 of each individual transition is greater than the cumulated emissions in the control land-use run (305 GtC). (1700-2100 contribution) is the difference control - zero between 1700 and 2100 in ppm. (1990-2100 contribution) is the difference control - zero between 1990 and 2100. The difference E1 - E2 quantifies the amplifier effect of land-use on atmospheric CO_2.

Land-use	1700-2100 period					Land-use	1990-2100 period				
transitions	(area)	(flux)	E1	E2	E1-E2	transitions	(area)	(flux)	E'1	E'2	E'1-E'2
f2a	1729	410	515	475	40	f2a	987	261	454	411	43
f2g	362	72	405	400	5	f2g	139	45	380	357	22
a2f	146	-32	371	376	-5	a2f	21	14	368	348	20
a2g	16	-0.25	383	383	-0	a2g	10	18	369	349	20
g2f	79	-10	381	381	0	g2f	74	9	367	346	21
g2a	1700	40	404	392	12	g2a	1214	49	387	356	31
control	4032	481	554	493	61	control	2445	305	483	425	58
zero	0	0	383	383	0	zero	0	18	369	349	20
(1700-2100 contribution)	-	-	171	110	61	(1990-2100 contribution)	-	-	114	76	38

61 % (E2), proving that land-use change act to amplify atmospheric CO_2 levels in response to fossil fuel emissions.

It can be seen that the transitions which contributes the most to the land-use amplifier effect on CO_2 is the clearing of forests through $f2a$ and $f2g$ processes (43 ppm), whereas conversion of grasslands to crop ($g2a$) contributes 12 ppm to the amplifier E1-E2. Those three conversions have in common to reduce the residence time of carbon in biomass and soils, or in both, concomitantly with a decrease of the carbon stocks. On the other hand, the three other transitions $a2f$, $a2g$, $g2f$, which increase terrestrial carbon stocks, act to additionally lower the increase in CO_2. For instance, an effect of -7 ppm by 2100 can be attributed to the reforestation of former croplands, that is also amplified by a correlated increase of the carbon residence times on the newly forested lands (5 ppm less of atmospheric CO_2 for the cropland-to-forest transition).

Note that the areas subject to land-use change are different for each transition in Table V, according to past and projected trends. The values of the net amplifying effect on CO_2 in 2100 are thus also relative to the importance of each particular transition in the global land-use scenario. For instance, $f2a$ and $g2a$ are dominant in the IPCC-A2 scenario, whereas transition $a2g$ is essentially marginal (cf. Table V). In table V, except for the "control" and "zero" experiments, only one land-use transition is introduced at the same time. Because the global amplifying effect depends on the CO_2 trajectory, the effect of 61 ppm in E1 is not rigorously equal to the sum of individual effects (52 ppm). The individual contribution of each transition within E1 is greater in absolute value than when this transition occurs alone, because the amplifier effect is also sensitive to the rate of increase of atmospheric CO_2 (see GC2003), that is higher in E1 than in each of the separate sensitivity tests.

4.2. Role of past and future land-use on future atmospheric CO_2 levels

In this section, we seek to separate the contribution of historical versus future land-use processes to atmospheric CO_2 levels by 2100. To do so, we performed a special set of simulations where, during the period 1700-1990, land-use change happens with all transitions, but after 1990, with only one transition at a time, or altogether (control run), or none (zero run). All those simulations are given prime symbols. The results are given in the right columns of Table V in terms of atmospheric increase cumulated for 1990-2100. Under the A2 scenario, the contribution of post-1990 land-use changes to future atmospheric CO_2 increase, obtained from the difference between "control" and "zero" runs is of 114 ppm. This means that future land-use does contribute 2/3 to the global calculated 1700-2100 atmospheric CO_2 rise specifically due to land-use (171 ppm, see former section).

Importantly, the "zero" simulation shows an amplifier effect of 20 ppm. Thus, even if we would stop by now all land-use activities, not only delayed emissions will be resilient for several decades, adding a source of 18 GtC after Table V, but also the amplifier effect is expected to increase with time, from about 3 ppm in 1990 up to 20 ppm by 2100. In other words, out of the 61 ppm amplifier effect projected in the A2 scenario by 2100, 20 ppm will happen just because of historical land-use. The reason for this is that the residence times of carbon have already been reduced by land-use in 1990, which implies for the future a lower CO_2 uptake by undisturbed ecosystems than the one that would be found assuming pre-industrial vegetation cover. The separate contribution of future land-use change to the amplification effect is thus of 38 ppm. As we can see in Figure 7, most of the amplifying effect is expected to be revealed in the future (58 ppm out of 61 ppm) because the magnitude of the effect depends on an initial signal which is the rate of increase in atmospheric CO_2, as for beta-factor driven biospheric uptake. As a consequence, we can also expect that, because of land-use practices that will occur during 1990-2100 in the scenario, CO_2 will continue to rise after 2100, even if fossil fuel emissions are eventually reduced.

5. Conclusion

In order to study the effects of land-use change on recent past and future atmospheric CO_2 levels, we have constructed a reduced-form global carbon cycle model. In this model, land-use processes, expressed into 6 transitions occurring between forests, pasture and croplands are driven by changes in areas, based upon which we calculate a carbon flux to or from the atmosphere. The area of each biome are taken from (Houghton and Hackler, 2001) over the historical period and adapted from the integrated model IMAGE 2.2 results for the future, with the IPCC scenario A2 being taken as a an example. The main land-use processes responsible for past and future increase in atmospheric CO_2 are in order of importance the clearing of forests to crops (410 GtC cumulated over 1700-2100), deforestation to pasture (72 GtC), and the ploughing of prairies into agriculture (40 GtC). Second, land-use change acts both to emit CO_2 to the atmosphere, and to reduce the residence time of carbon in the biosphere. Because of this, we found that the projected CO_2 levels by 2100 are higher (by 61 ppm) when land-use processes are included consistently within the global carbon cycle, rather than if the vegetation cover is assumed to stay pre-industrial (i.e. land-use emissions treated as fossil emissions). It is higher than in our former study where the role of pasture and grasslands was neglected. For the high land-use intensity scenario A2, this amplifier effect of land-use on atmospheric CO_2 is likely to be maximal. We examined the sensitivity of this result to the hypothesis that NPP is not correlated to atmospheric CO_2 concentrations: in such cases, the amplifying effect is lower, but globally atmospheric CO_2 ends up being much higher (up to 150 ppm for IPCC A2 if the net primary productivity of all biomes stays to its 1990 levels), because of reduced carbon sequestration in the terrestrial biosphere. The two main practices which contribute most to the land-use amplifier effect are the clearing of forests to crop and pasture, with grassland-crop conversion having a smaller role. Additionally, we showed that land-use which has already occurred prior to 1990 will account for 20 ppm additional CO_2 by 2100, ie 30% of the amplifier effect on atmospheric CO_2 by 2100.

These results suggest that there might exist an additionnal carbon benefit associated to preserving existing pristine forests with high carbon residence times. Future atmospheric CO_2 rise will be primarily determined by fossil emission rates, but preventing deforestation is proportionnally more efficient: it lowers the land-use source, and might preserve the sink capacity of the terrestrial biosphere. However, the present implementation of the Kyoto Protocol does not create any incentive for such a preservation effort (Schulze et al., 2002; Schulze et al., 2003). Future work will include studying the amplifier effect when inferring fossil fuel emissions compatible with atmospheric CO_2 stabilisation targets, and describing the impact of forest management practices and the use of biofuels on future atmospheric CO_2 trends.

6. Appendix: Description of the land-use change carbon book-keeping model

Land-use transitions occur between forests, grasslands and croplands within one (k, l) grid-point defined by the pertaining IPCC region $k = 1..4$, and climatic zone $l = 1..3$. We here describe explicitly the structure of the land-use book-keeping model in a generic (k, l) grid-point. As the model's structure is the same in each grid-point, we will drop for clarity purpose all references to the indexes (k, l), that may be added to all of the variables hereafter – at the exception of global ones such as atmospheric CO_2. We define age-classes for surfaces in transition between biomes, representing the time in years for a newly affected ecosystem to reach an "equilibrium" state after the transition. Three such "time to equilibrium" are defined, for new forests τ_f, new agricultural land τ_a, new grasslands τ_g. After leaving age-class τ_x, a biome enters the final "equilibrium" age-class, also referred as "undisturbed". This special age-class, noted u, contains biomes that are no more considered as "in transition": its carbon budget is balanced between input and output, in absence of any mechanism that creates an increase in NPP.

Evolution of surfaces

Let $s_{x,\tau}$ be the surface of biome $x \in \{f, a, g\}$ in age class $\tau \in \{1, 2, ..., \tau_x, u\}$, where the index u is the final class corresponding to carbon "equilibrium". We note $ds_{x2y}(t)$ the prescribed area converted during year t from biome $x \in \{f, a, g\}$ to biome $y \in \{f, a, g\}$, $y \neq x$. In the following equations, y and z will be considered as generic elements of $\{f, a, g\}$, different of $x \in \{f, a, g\}$, so that $\sum_{y\in\{f,a,g\}\ y\neq x}$ will be written $\sum_y$ for simplicity purpose. In the time period between t and $t + 1$, the evolution of the area of the different age classes of biome $x \in \{f, a, g\}$ is given by:

$$\begin{aligned} & s_{x,1}(t+1) = \sum_y ds_{y2x}(t) \\ & \forall \tau \in [2, \tau_x], \;\; s_{x,\tau}(t+1) = s_{x,\tau-1}(t) \\ & s_{x,u}(t+1) = s_{x,u}(t) + s_{x,\tau_x}(t) - \sum_z ds_{x2z}(t) \end{aligned} \tag{1}$$

Past land-use changes are separately accounted for at each annual period up to τ_x years after the transition, and also after, but in an aggregated way, when recovered biomes enter the "undisturbed" class.

Evolution of biomass stocks

We note $B_{x,\tau}(t)$ the standing biomass resident on each surface $s_{x,\tau}$ of age-classes $\tau \in \{1, 2, ..., \tau_x, u\}$, and $\eta(C)$, net primary productivity, function of the atmospheric CO_2 concentration $C(t)$:

$$\eta_{x,\tau}(t) = \eta_{x,\tau}^{t=0}\left(1 + \beta \log\frac{C(t)}{C(0)}\right) \tag{2}$$

where β is a global value just as $C(t)$. The biomass mortality is assumed to be a constant fraction μ_x of the standing biomass. The evolution of $B_{x,\tau}(t)$ is given by:

$$
\begin{aligned}
&B_{x,1}(t+1) = (1-\mu_x)\ \eta_{x,1}(C)\ \sum_y ds_{y2x}(t)\\
&\forall \tau \in [2,\tau_r], B_{x,\tau}(t+1) = (1-\mu_x)\Big[B_{x,\tau-1}(t) + \eta_{x,\tau}(C)s_{x,\tau}(t+1)\Big]\\
&B_{x,u}(t+1) = (1-\mu_x)\Big[B_{x,\tau_x}(t) + \eta_{x,u}(C)s_{x,u}(t+1)\\
&\qquad\qquad + B_{x,u}(t)\Big(1 - \frac{\sum_z ds_{x2z}(t)}{s_{x,u}(t)}\Big)\Big]
\end{aligned}
\tag{3}
$$

During the $x2y$ transition, a fraction α_{x2y} of the standing biomass is left on site to enter the soil carbon pool. The rest is oxidized within one year and returns to the atmosphere. For forest clearing, a fraction ω_{f2y} of destroyed biomass is not oxidized but directed into woods products pools (see below).

Evolution of soil carbon stocks

The soil carbon content $S_{x,\tau}(t)$ "follows" the surface change. It is affected by land-use change both (i) immediately, because some of the cleared biomass is left on site, and (ii) in a delayed manner, because land-use affects the respiration rate $\delta_{x,\tau}$ of soil carbon, and modifies the annual dead biomass export to the soil. The evolution of vintaged soil carbon pools is given by:

$$
\begin{aligned}
&S_{x,1}(t+1) = (1-\delta_{x,1})\Big[\sum_y \Big(\alpha_{y2x}B_{y,u}(t) + S_{y,u}(t)\Big)\frac{ds_{y2x}(t)}{s_{y,u}(t)}\\
&\qquad\qquad + \mu_x\eta_{x,1}(C)\sum_y ds_{y2x}(t)\Big]\\
&\forall \tau \in [2,\tau_x],\quad S_{x,\tau}(t+1) = (1-\delta_{x,\tau})\Big[S_{x,\tau-1}(t) + \mu_x\eta_{x,\tau}(C)s_{x,\tau}(t+1)\Big]\\
&S_{x,u}(t+1) = (1-\delta_{x,u})\Big[S_{x,\tau}(t) + S_{x,u}(t)\Big(1 - \sum_z \frac{ds_{x2z}(t)}{s_{x,u}(t)}\Big)\\
&\qquad\qquad + \mu_x\eta_{x,u}(C)s_{x,u}(t+1)\Big]
\end{aligned}
\tag{4}
$$

Evolution of wood products pools

During deforestation, a fraction ω^{10}_{f2y} (resp. ω^{100}_{f2y}) , $y \in \{a, g\}$ of the forest biomass not left on site, is harvested and directed into wood products pools W^{10} (resp. W^{100}) of 10 years (resp. 100 years) exponential decay time, whose evolution is given by:

$$W^{10}(t+1) = \frac{9}{10}W^{10}(t) + \sum_y \omega^{10}_{f2y}(1-\alpha_{f2y})\frac{ds_{f2y}(t)}{s_{f,u}(t)}B_{f,u}(t)$$
$$W^{100}(t+1) = \frac{99}{100}W^{100}(t) + \sum_y \omega^{100}_{f2y}(1-\alpha_{f2y})\frac{ds_{f2y}(t)}{s_{f,u}(t)}B_{f,u}(t) \quad (5)$$

Terrestrial carbon fluxes

Each year, over each sub-region, we have an "instantaneous" land-use source $\phi_i(t)$ to the atmosphere, due to the oxidation (eg burning) of a fraction of the disturbed biomass neither left on site, nor transformed to wood products:

$$\begin{aligned}\phi_i(t) &= \sum_{y\neq f}(1-\omega^{10}_{f2y}-\omega^{100}_{f2y})(1-\alpha_{f2y})\frac{ds_{f2y}(t)}{s_{f,u}(t)}B_{f,u}(t)\\ &+ \sum_{(x,y),\ x\neq y,\ x\neq f}(1-\alpha_{x2y})\frac{ds_{x2y}(t)}{s_{x,u}(t)}B_{x,u}(t)\end{aligned} \quad (6)$$

A "delayed" land-use source $\phi_d(t)$ is defined as the sum of (i) the flux due to the difference between NPP and RH over lands in transition to a new biome as well as over croplands, and (ii) the flux from decaying wood products:

$$\begin{aligned}\phi_d(t) &= \sum_x \sum_{\tau=1,\ldots,\tau_x}(S_{x,\tau}(t)\delta_{x,\tau} - \eta_{x,\tau}(C)s_{x,\tau}(t))\\ &+ S_{a,u}(t)\delta_{a,u} - \eta_{a,u}(C)s_{a,u}(t)\\ &+ \frac{1}{10}W^{10}(t) + \frac{1}{100}W^{100}(t)\end{aligned} \quad (7)$$

Finally, the "residual" terrestrial uptake $\phi_{au}(t)$ (undisturbed lands) is equal to the carbon balance of undisturbed forests and grasslands:

$$\phi_{au}(t) = s_{f,u}(t)\eta_{f,u}(C) - \delta_{f,u}S_{f,u}(t) + s_{g,u}(t)\eta_{g,u}(C) - \delta_{g,u}S_{g,u}(t) \quad (8)$$

Global carbon budget

Overall, the evolution of atmospheric CO_2 between t and $t+1$ (one year), is given by:

$$C(t+1) - C(t) = E(t) - s_{oc}\phi_{as}(t) + \sum_{k=1}^{4}\sum_{l=1}^{3}(\phi^{k,l}_i(t) + \phi^{k,l}_d(t) - \phi^{k,l}_{au}(t)) \quad (9)$$

where $E(t)$ are the global fossil CO_2 emissions in year t, $s_{oc} = 3.62 \times 10^{14}\mathrm{m}^2$ is the ocean's area, and ϕ_{as} is the net air-sea flux per unit area in year t (see GC2003 or (Joos et al., 1996) for the description of the air-sea calculation).

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